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MECHANICAL PROPERTIES OF HIGH-MANGANESE SEMIKILLED STEEL PLATE

SSC-144

BY
R. W. VANDERBECK

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2 January 1963

Dear Sir:

Herewith is Ship Structure Committee Report SSC 144: Mechanical Properties of High-Manganese Semikilled Steel Plate, by Mr. R. W. Vanderbeck. This is the final report of a project to evaluate the mechanical properties of production heats of low-carbon, high-manganese semikilled steels of possible use in ship building.

This project was jointly sponsored by the Ship Structure Committee and the United States Steel Corporation, and was conducted under the guidance of the Committee on Ship Steel of the National Academy [illegible] Research Council.

This report is being distributed to the individuals and agencies associated with the project, and to those interested in the Ship Structure Committee program. Questions or comments regarding this report would be appreciated and should be sent to the Secretary, Ship Structure Committee.

Sincerely yours,

T. J. Fabik

T. J. FABIK
Rear Admiral, U. S. Coast Guard
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Serial No. SSC-144

Final Report
of
Project SR-141

to the

SHIP STRUCTURE COMMITTEE

on

MECHANICAL PROPERTIES OF HIGH-MANGANESE SEMIKILLED STEEL PLATE

by

R. W. Vanderbeck

Applied Research Laboratory
U. S. Steel Corporation

transmitted through

Committee on Ship Steel
Division of Engineering and Industrial Research
National Academy of Sciences-National Research Council

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Washington, D. C.
U.S. Department of Commerce, Office of Technical Services
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ABSTRACT

Test results obtained on seven production heats of semikilled steel containing 0.20% maximum carbon and 1.00 to 1.35% manganese indicate that as-rolled plates of this composition in thicknesses over 1 to 1-1/2 in. would meet the American Bureau of Shipping tensile requirements but might not have sufficient notch toughness to be considered a suitable substitute for as-rolled ABS Class C steel in thicknesses over 1 in. The results of V-notch Charpy and drop-weight tests were not in complete agreement, and drop-weight transition temperatures obtained with full-plate-thickness specimens were appreciably higher than those obtained with specimens of reduced thickness. The most favorable interpretation of notch-toughness behavior was obtained using drop-weight tests with 1-in.-thick specimens, and, on this basis, the experimental steel in thicknesses over 1 to 1-1/2 in., inclusive, was about as suitable as ABS Class B steel in its maximum thickness of 1 in. It is believed that further testing is needed to determine the best test and testing techniques for evaluating the service performance of plates over 1 in. thick. It does appear, however, that this experimental steel in the normalized condition would be sufficiently notch tough to allow its substitution for either as-rolled or normalized Class C steel, if warranted by economic and other considerations.

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INTRODUCTION

In 1956, Harris and Williams[1] issued a report that was prepared under the guidance of the Committee on Ship Steel of the National Academy of Sciences-National Research Council for the Ship Structure Committee on the Metallurgical and Economic Aspects of Ship Steels and their Relation to Ship Failures. In the report, it is recommended that consideration be given to the development of a low-carbon, high-manganese, hot-rolled, semikilled plate steel that could be used as an alternate or as a substitute for American Bureau of Shipping (ABS) Class C steel. A semikilled substitute for ABS Class C steel, which is a killed steel used in thicknesses over 1 in., is considered essential during a national emergency because of the limited hot topping capacity available in the United States for the production of killed steel. Harris and Williams concluded from their analysis of the notch toughness behavior of plates that failed in ship service that the new steel would be virtually free from brittle fracture if it had an average 15 ft-lb V-notch Charpy transition temperature not exceeding 10 F.

During the period in which the above report was being prepared, experimental results were obtained on plate product from two 25-ton basic-open-hearth semikilled heats containing relatively low C and high Mn content.[2] The results indicate that the desired notch toughness properties could be obtained in plate over 1 in. to 1-3/4 in. thick containing a maximum of about 0.20% C and about 1.00 to 1.35% Mn content. It was also desired to maintain the tensile properties specified by ABS, and the above composition seemed to meet this requirement. On the basis of these promising results, Harris and Williams recommended "a program aimed at gaining production experience with a proposed semikilled alternative for ABS Class C steel."

Accordingly, the Committee on Ship Steel outlined a program to produce a number of production open-hearth heats of the low-carbon, high-manganese, semikilled variety so that production experience could be obtained and the plate product evaluated.

The present study describes the test results obtained on seven 300-ton

open-hearth heats of the proposed experimental semikilled steel.

MELTING AND PROCESSING OF HEATS

The seven heats of semikilled steel were melted and rolled to plate product at the Homestead District Works of United States Steel Corporation. All heats were melted to meet the general composition requirements of 0.20% maximum C and 1.00 to 1.35% Mn content. Heats A, B, and C were melted to aim C contents of 0.12, 0.16, and 0.20%, respectively, so that the optimum C content for meeting the ABS tension-test requirements could be determined. Inasmuch as Heat B exhibited the most suitable combination of tensile properties of the three heats, the remaining four heats, D, E, F, and G, were melted to an aim C content of 0.16%.

The experimental plates were rolled to thicknesses of 3/4, 1-1/4, and 1-1/2 in. on all seven heats and also to a thickness of 1 in. on the first three heats. Major interest was in the heavier thicknesses, but the 3/4-in. plates were produced so that a direct comparison could be made with 3/4-in. ABS Class B steel. The plates were rolled from one or more ingots selected near the middle of each heat, and the location of the test samples with regard to position of the plate in the ingot is given in Table 1.

Product yield from ingot to plate for these steels was considered normal and not materially different from that obtained on ABS Class B semikilled steel.

TESTS CONDUCTED

The various organizations that conducted tests on these steels in this cooperative program were United States Steel Corporation (USS), American Bureau of Shipping (ABS), Naval Research Laboratory (NRL), New York Naval Shipyard (NYNSY), and Watertown Arsenal (Wat. Ars.). The tests conducted by these organizations are outlined in Table 2. The heats that were tested by each participant are indicated by the appropriate letter designations for the heats. As indicated in this table and Table 1, some tests were performed on the normalized product in addition to the tests on the plates in the as-rolled condition.

TABLE 1

LOCATION OF PLATE SAMPLES TESTED

Heat	Plate Thickness, in.	Ingot	Position of Slab in Ingot	Plate Cut	Tested By
A, B, C	3/4	R	Middle	Top	USS
		R	Middle	Bottom*	Others
	1	S	Top	Top	USS
	1-1/4	S	Middle	Top	USS
		S	Middle	Bottom*	Others
	1-1/2	S	Bottom	Bottom	USS
		T	Middle	Whole Slab*	Others
D, E	3/4	R	Top	Top	USS
		R	Top	Middle**	Others
		R	Top	Bottom	USS
	1-1/4	R	Middle	Top	USS
		R	Middle	Bottom**	Others
	1-1/2	R	Bottom	Top**	Others
		R	Bottom	Bottom	USS
F, G	3/4	R	Top	Top	USS
	1-1/4	R	Middle	Top	USS
	1-1/2	R	Bottom	Bottom	USS

No asterisk - Tests on hot-rolled product.
* - Tests on hot-rolled product from Heats A, B, C, and on normalized product from Heat A.
** - Tests on hot-rolled and normalized product.

The crack-starter drop-weight test has been adequately described by Puzak and Babecki,[3] and any departure from the normalization procedures described in the reference will be called to attention. The transition temperature measured (NDT) is meant to be a crack initiation temperature (like the 15 ft-lb V-notch Charpy temperature) below which brittle fracture may be readily initiated.

The crack-starter explosion tests developed by Puzak and Pellini[4] were used in this instance to determine the fracture-arrest temperature above which

TABLE 2

HEATS TESTED AND TESTS CONDUCTED BY THE VARIOUS INVESTIGATORS

	Investigating Laboratory					
	As-Rolled Plate				Norm. Plate	
Type Test	USS	NRL	ABS	NYNSY	Wat. Ars.	NYNSY
Chemical Analysis	A thru G	A, B, C	A, B, C			
Tensile Properties	A thru G		A, B, C			
Ferrite Grain Size	A thru G					
V-Notch Charpy	A thru G	A thru E	A, B, C		A, D, E	
Drop-Weight	A thru G	A thru E			A, D, E	
Crack-Starter Explosion		A thru E				
van der Veen				A, D, E		A, D, E
Low-Blow					A, D, E (3/4")	
Underbead-Cracking	A thru G					

crack propagation would be unlikely under elastic loading. This temperature is called FTE, the fracture transition temperature for elastic loading.

The van der Veen test[5] also defines a fracture transition temperature, which is selected at that temperature at which the depth of shear fracture below the notch is 32 mm. Since the net section below the notch is 67 mm, the transition temperature is, in effect, selected at a temperature corresponding to approximately 50% shear fracture appearance.

The low-blow V-notch Charpy test[6] also defines a crack-arrest or fracture transition temperature.

The underbead-cracking test[7] was used to determine the amount of cracking that could occur in the heat-affected zone of a weldment made with cellulose-coated electrodes at various initial plate temperatures. The percentage of cracking observed is usually higher than that found in commercial weldments because of the low heat input employed and the resulting high cooling

TABLE 3

ABS COMPOSITION AND STRENGTH REQUIREMENTS

ABS Specification	Plate Thickness, in.	Composition, per cent					
		Specified			Typical		
		C	Mn	Si	C	Mn	Si
Before 1948	All	--	--	--	0.24	0.44	--
1948 Class A	to 1/2	--	--	--	0.23	0.50	
1948 Class B	Over 1/2 to 1	0.23 max	0.60-0.90	--	0.19	0.75	
1956 Class B	Over 1/2 to 1	0.21 max	0.80-1.10	--	0.17	0.95	
1962 Class B	Over 1/2 to 1	0.21 max	0.80-1.10[A]	--			
1948 Class C	Over 1	0.25 max	0.60-0.90	0.15-0.30*	0.18	0.75	0.22*
1956 Class C	Over 1	0.24 max	0.60-0.90	0.15-0.30*	0.18	0.75	0.22*
1962 Class C	Over 1 to 2[B]	0.23 max[C]	0.60-0.90[A]	0.10-0.35			

*Fine-grain practice

[A]Upper limit of Mn may be exceeded provided C + (Mn/6) is not greater than 0.40.

[B]Where plates of over 1-3/8 in. thickness are used in important structural parts, it may be required that such plates be produced to special specifications. Plates over 2 in. in thickness are to be produced to specially agreed upon specifications.

[C] Plates specified to be normalized may have a maximum carbon of 0.24.

	Tension-Test Requirements		
	Yield Point psi	Tensile Strength, psi	Elongation in 8 in. %
1956	32,000 min	58,000 to 71,000	21 min
1962	--	58,000 to 71,000	21 min

rate in the test specimens. The percentage of cracking is equal to the length of the cracked area times 100 and divided by the total length of the weld bead.

DISCUSSION OF TEST RESULTS

Throughout this report, reference will be made to the steels produced to the 1956 ABS specification requirements, and the properties of the ABS steels will be compared with those of the experimental steels reviewed here. For ready reference, therefore, the ABS composition and strength requirements are listed in Table 3. It will be noted that the composition requirements were revised in 1948, 1956 and in 1962. The 1956 Class B steel, which is limited to thicknesses

TABLE 4

USS CHECK CHEMICAL ANALYSES OF PLATES AT THE QUARTER-WIDTH POSITION

Heat	Plate Thickness, in.	C	Mn	P	S	Si	Cu	Ni	Cr	Total Al	Total N
A	3/4	0.12	1.25	--	--	0.031	--	--	--	--	--
	1	0.13	1.30	0.016	0.034	0.030	0.06	0.08	0.03	0.005	0.006
	1-1/4	0.12	1.29	--	--	0.028	--	--	--	--	--
	1-1/2	0.10	1.22	0.015	0.024	0.040	0.06	0.08	0.03	0.008	0.004
B	3/4	0.16	1.25	--	--	0.025	--	--	--	--	--
	1	0.20	1.39	0.015	0.030	0.024	0.04	0.06	0.01	0.003	0.005
	1-1/4	0.16	1.26	--	--	--	--	--	--	--	--
	1-1/2	0.14	1.24	0.014	0.019	0.026	0.03	0.03	0.01	0.009	0.003
C	3/4	0.21	1.31	--	--	0.026	--	--	--	--	--
	1	0.24	1.38	0.016	0.040	0.030	0.05	0.09	0.02	0.004	0.006
	1-1/4	0.21	1.34	--	--	0.027	--	--	--	--	--
	1-1/2	0.19	1.39	0.015	0.030	0.030	0.05	0.09	0.02	0.010	0.005
D	3/4 Top	0.18	1.28	0.019	0.032	0.034	--	--	--	--	--
	3/4 Bottom	0.19	1.28	0.018	0.032	0.032	--	--	--	--	--
	1-1/4	0.20	1.29	0.019	0.035	0.034	--	--	--	0.006	0.005
	1-1/2	0.15	1.23	0.018	0.028	0.050	--	--	--	--	--
E	3/4 Top	0.15	1.18	0.015	0.029	0.024	--	--	--	--	--
	3/4 Bottom	0.16	1.20	0.018	0.035	0.028	--	--	--	--	--
	1-1/4	0.16	1.19	0.019	0.038	0.020	--	--	--	0.004	0.005
	1-1/2	0.14	1.16	0.016	0.031	0.028	--	--	--	--	--
F	3/4	0.21	1.27	0.013	0.025	0.04	--	--	--	--	--
	1-1/4	0.19	1.25	0.015	0.022	0.01	--	--	--	0.003	0.006
	1-1/2	0.17	1.23	0.015	0.019	0.03	--	--	--	--	--
G	3/4	0.21	1.10	0.014	0.027	0.02	--	--	--	--	--
	1-1/4	0.19	1.10	0.015	0.023	0.02	--	--	--	0.003	0.005
	1-1/2	0.16	1.06	0.016	0.020	0.01	--	--	--	--	--

over 1/2 to 1 in., inclusive, is fairly close in composition to the experimental steels, but would have on the average about 0.20 or 0.25% less Mn.

Composition

Check analyses performed by USS on the various plate samples of the seven heats are given in Table 4. The 1 1/2-in.-thick plate (bottom cut from bottom slab) of Heat A, which was melted to the lowest C content, exhibited the lowest C content (0.10%) of all the plates, and the one-in. plate (top cut from top slab) of Heat C, which was melted to the highest C content, exhibited the highest C content (0.24%). The observed extremes in C content are consistent with the usual observation that the bottom of an ingot shows the lowest C content and the top, the highest. The other plates were in the range of 0.12

TABLE 5

TENSILE PROPERTIES

		Edge of Plate			Quarter Line of Plate			Center Line of Plate		
Steel	Plate Thickness, in.	Yield Point, psi	Tensile Strength, psi	Elongation in 8 in. %	Yield Point, psi	Tensile Strength, psi	Elongation in 8 in. %	Yield Point, psi	Tensile Strength, psi	Elongation in 8 in. %
A	3/4	38,300	62,200	33.5	37,300	62,200	31.2	37,500	62,800	32.5
	1	35,400	61,700	37.7	35,600	62,700	30.0*	37,700	62,400	36.5
	1-1/4	34,200	61,100	36.2	34,500	61,900	38.5	34,900	62,000	37.2
	1-1/2	32,300	58,100	39.5	30,200	56,100	39.0	31,900	56,200	38.7
B	3/4	40,100	68,600	33.7	40,200	68,200	31.7*	38,700	67,700	34.0*
	1	41,400	68,000	33.7	44,300	74,300	27.0	45,100	75,600	25.0*
					42,300	74,100	31.0	44,200	75,100	30.5
	1-1/4	36,800	66,800	33.7*	35,600	66,700	35.7	36,300	66,400	36.0
	1-1/2	36,700	63,500	34.2*	34,200	61,900	35.0	33,000	61,300	35.2
C	3/4	45,600	74,100	29.2	45,700	74,700	29.2	45,300	74,400	30.0
	1	42,600	72,800	31.7	45,300	79,800	26.5	46,200	81,300	20.0*
					42,100	80,800	29.5	45,600	82,200	28.0
	1-1/4	39,600	72,700	31.5	41,000	72,200	32.5	40,300	71,400	32.7
	1-1/2	42,500	70,900	35.2	38,000	68,200	35.2	37,600	67,200	34.2
D	3/4 Top	39,800	67,900	31.0	39,300	67,700	34.0	40,200	67,700	30.0
	3/4 Bottom	38,700	68,400	30.0	42,200	71,200	29.0	40,500	71,000	30.0
	1-1/4	37,100	68,000	34.0	37,600	69,800	35.0	38,300	68,900	24.0
	1-1/2	35,000	65,600	36.0	34,000	64,500	36.0	33,400	64,400	35.0
E	3/4 Top	35,300	62,500	33.0	37,100	62,300	34.0	36,000	61,000	28.0
	3/4 Bottom	36,000	62,200	33.0	37,400	64,700	31.0	39,200	64,400	30.0
	1-1/4	33,100	61,700	34.0	33,500	64,000	38.0	33,500	64,000	34.0
	1-1/2	32,300	61,700	37.0	33,200	60,600	38.0	33,400	60,900	38.0
F	3/4	44,300	70,800	35.0	44,800	74,200	31.5	44,400	73,500	32.0
	1-1/4	38,800	69,800	35.5	39,200	68,700	37.5	38,400	68,200	36.0
	1-1/2	35,500	66,100	39.0	34,200	65,400	39.0	35,000	65,100	38.0
G	3/4	42,200	66,000	36.0	40,300	69,000	34.0	40,800	69,900	32.0
	1-1/4	34,100	64,500	38.0	35,600	65,900	32.0	34,000	64,400	39.5
	1-1/2	32,900	61,600	40.0	32,700	60,100	40.5	33,200	59,800	41.0

NOTE: All values reported are for single tests. Yield-point values are based on upper-yield-point loads determined by "drop-of-the-beam" method.

* Broke within 2 inches of gage mark.

to 0.21% C content. The Mn content of the plate samples averaged 1.25%, about 0.30% greater than the average Mn content of the present ABS Class B steel.

Some chemical analyses were also performed by ABS and NRL, but they have not been reported here since the results are similar to those obtained by USS.

Tensile Properties

The individual tension-test results are presented in Table 5. The variation in yield point, tensile strength, and elongation with C content is plotted in Fig. 1 for the 3/4-in.-thick plates, in Fig. 2 for the 1-in.-thick plates, in Fig. 3 for the 1 1/4-in.-thick plates, and in Fig. 4 for the 1 1/2-in.-thick plates.

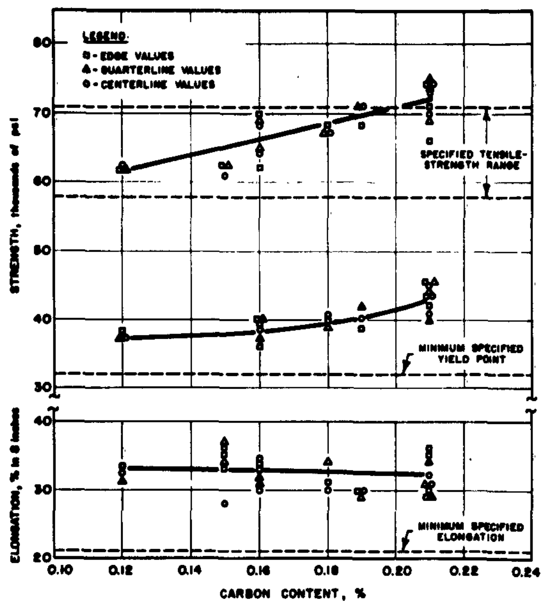

FIG. 1. VARIATION IN TENSILE PROPERTIES WITH C CONTENT FOR 3/4-IN.-THICK PLATES.

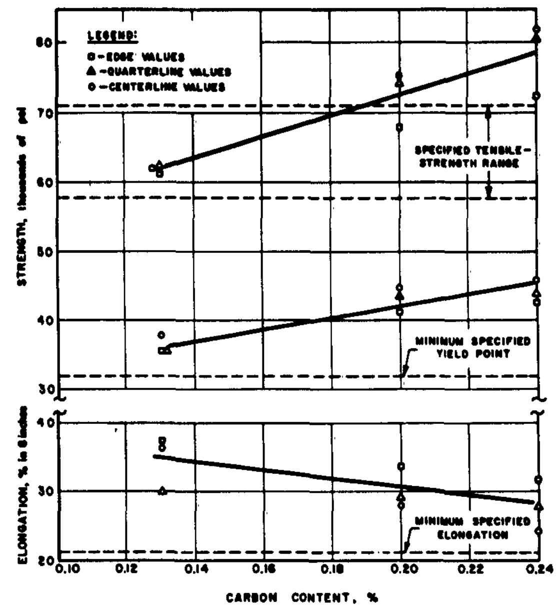

FIG. 2. VARIATION IN TENSILE PROPERTIES WITH C CONTENT FOR 1-IN.-THICK PLATES.

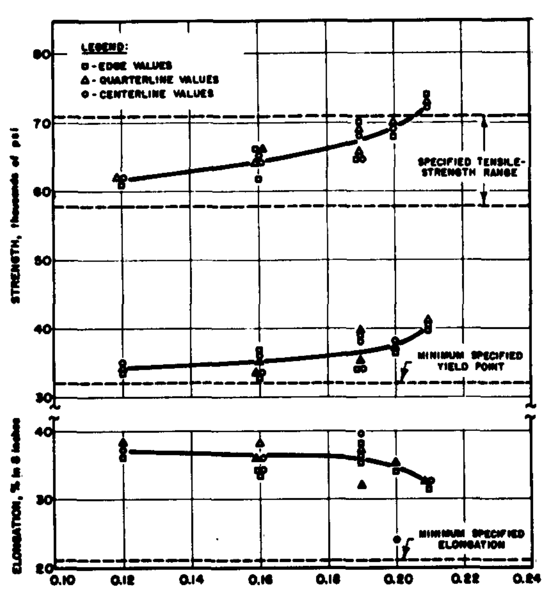

FIG. 3. VARIATION IN TENSILE PROPERTIES WITH C CONTENT FOR 1-1/4-IN.-THICK PLATES.

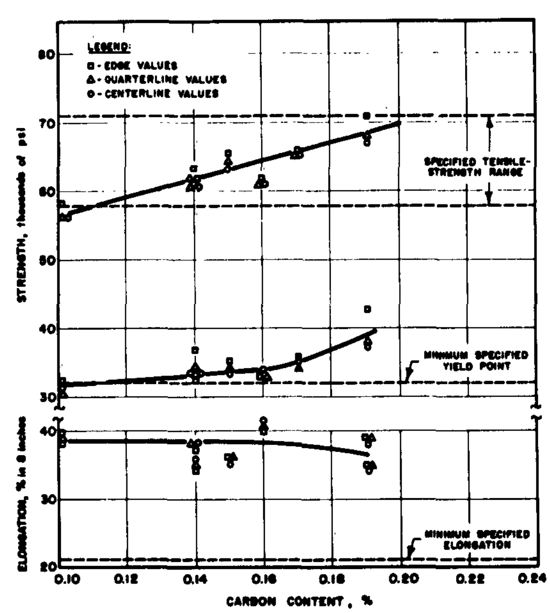

FIG. 4. VARIATION IN TENSILE PROPERTIES WITH C CONTENT FOR 1-1/2-IN.-THICK PLATES

Figure 1 shows that the minimum yield point, tensile strength, and elongation specified by ABS were readily met by the 3/4-in. plate for the carbon contents investigated (0.12 to 0.21%). At the highest C content of 0.21%, the tensile strength of five of the nine 3/4-in. plates exceeded the maximum tensile strength of 71,000 psi.

The 1-in. plates were top-plate cuts from top slabs, and, as indicated in Table 4, the carbon contents in these plates for Heats B and C were higher due to chemical segregation than in plates from other ingot positions. Figure 2 for the 1-in. plates shows that the tensile strength at 0.20% C was higher on the average than the tensile strength for the 3/4-in. plates at the same carbon level. The strength at the edge-of-the-plate position, moreover, was substantially lower than the strength at the quarterline and centerline positions. This behavior seems to be associated with variations in the degree of chemical segregation, and less reliance will therefore be placed on the results from these 1-in. plate samples, which involve only 3 heats, than on the results from the other plate thicknesses, which involve 7 heats.

The 1 1/4-in. plates in Fig. 3 exhibited essentially the same variation in tensile properties with carbon content as the 3/4-in. plates except that the yield strength was about 3000 psi lower, the tensile strength about 1000 psi lower, and the elongation about 4% higher. The 1 1/2-in. plates in Fig. 4 exhibited a further decrease in strength and increase in elongation, and the minimum strength requirements would probably not be met with less than about 0.12% C.

In general, the results indicate that the experimental low-carbon, high-manganese, hot-rolled semikilled steel would meet ABS tension test specifications in plate thicknesses over 1 through 1-1/2 in., provided the C content is between 0.12 and 0.20% and the Mn content between 1.00 and 1.35%. The best aim C content to meet the tension-test specifications appears to be about 0.16%.

V-Notch Charpy Impact Tests

V-notch Charpy impact test results for the specimens prepared and tested by USS are listed in Table A-1 of the Appendix. These tables give both

the individual energy absorption values and the fracture appearance of the broken specimens. The energy absorption values for Heat A show considerable scatter. Heat A, however, has the lowest C content (0.12%), and it is not considered unusual for such scatter to occur when the transition temperature curve rises so steeply from low to high average energy values as it does for a low-carbon steel.[8] Chemical segregation may contribute to this behavior. The abrupt rise in energy seems in any event to be a favorable circumstance, even if accompanied by increased scatter.

Curves showing the variation in energy absorption with testing temperature are plotted from the above data in Figs. 5, 6, 7, and 8 for the four different plate thicknesses. In Fig. 5 for the 3/4-in. plate, note that two locations were tested for Heats D and E, as indicated. These locations are the top and bottom cuts of the top plate or slab of the ingot. On these figures, typical curves representing the average behavior of the plate thickness involved are also drawn. These typical curves are replotted in Fig. 9 to show the trends of impact behavior for each plate thickness. An average curve has not been drawn for the 1-in. plate because of the small amount of data and the chemical segregation in these particular samples.

The typical V-notch Charpy impact curves for the 1 1/4- and 1 1/2-in.-thick experimental plates are compared in Fig. 10 with average curves for other ABS grades of steel made to present and past specifications. The information on the ABS grades is taken mainly from an article by D. P. Brown.[9] Two average curves are shown for 1956 Class B steel, one based upon 19 plates tested by ABS and the other upon 7 plates produced and tested by USS. It will be noted that the V-notch Charpy behavior of the experimental steel in 1 1/4-in. thickness is similar to that of present-day 1956 Class B steel (over 1/2 to 1 in. thick). The notch-toughness curve for the 1 1/2-in. experimental steel is 10 to 20 F higher in temperature than that for the 1 1/4-in. plate.

Charpy V-notch impact tests were also conducted by ABS on Heats A, B, and C and by NRL on Heats A, B, C, D, and E for 3/4-, 1 1/4-, and 1 1/2-in.-thick plate. Average ABS and NRL data for Heats A, B, and C are plotted with USS data in Figs. 11, 12, and 13 to show the extent of agreement among

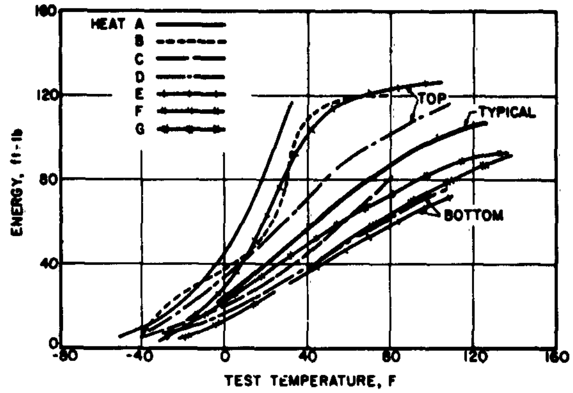

FIG. 5. V-NOTCH CHARPY CURVES FOR 3/4-IN.-THICK PLATES

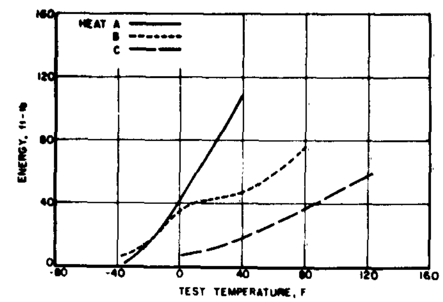

FIG. 6. V-NOTCH CHARPY CURVES FOR 1-IN.-THICK PLATES

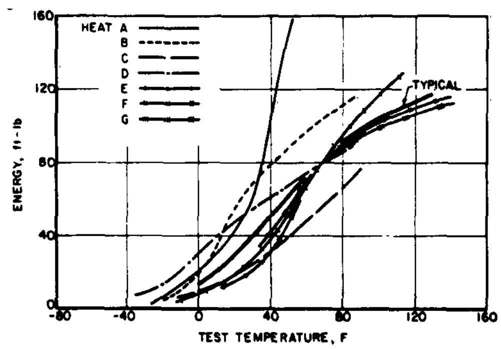

FIG. 7. V-NOTCH CHARPY CURVES FOR 1-1/4-IN.-THICK PLATES

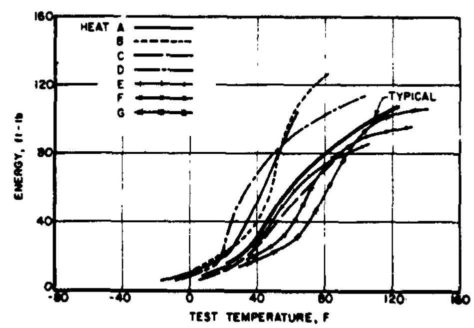

FIG. 8. V-NOTCH CHARPY CURVES FOR 1-1/2-IN.-THICK PLATES

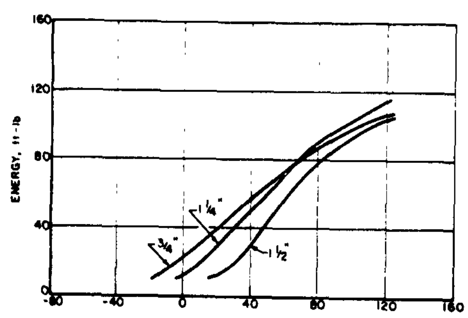

FIG. 9. TYPICAL V-NOTCH CHARPY CURVES FOR THE DIFFERENT PLATE THICKNESSES

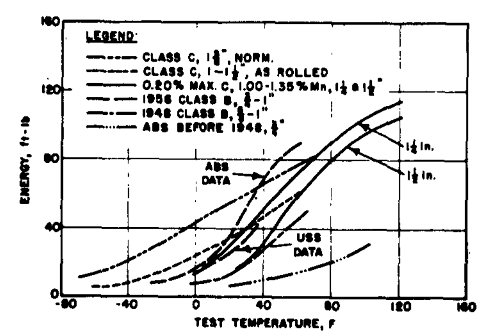

FIG. 10. TYPICAL V-NOTCH CHARPY CURVES FOR EXPERIMENTAL AND ABS STEELS

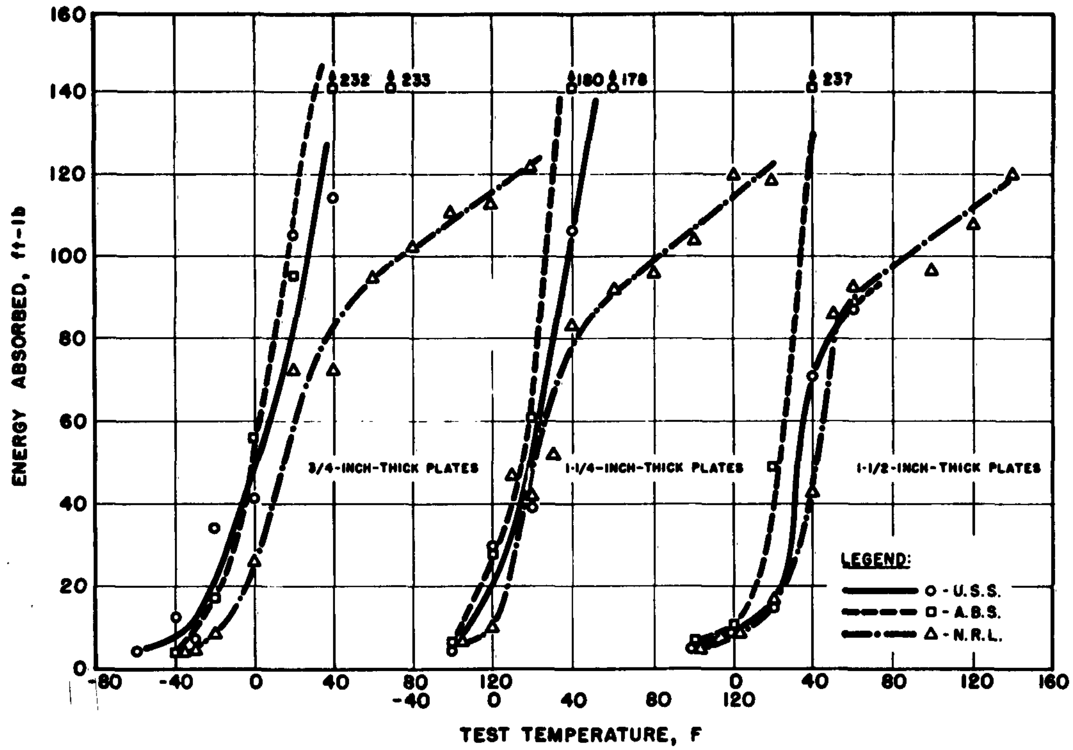

FIG. 11. CHARPY V-NOTCH CURVES FOR HEAT A, TESTED AT DIFFERENT LABORATORIES

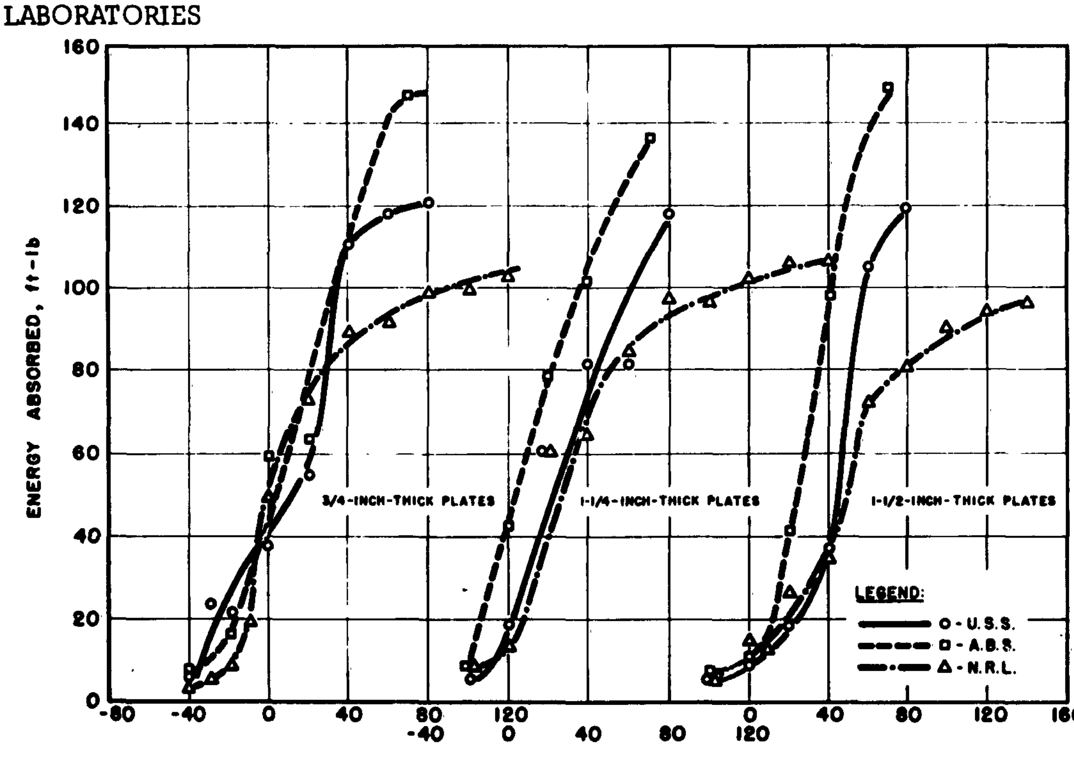

FIG. 12. CHARPY V-NOTCH CURVES FOR HEAT B, TESTED AT DIFFERENT LABS.

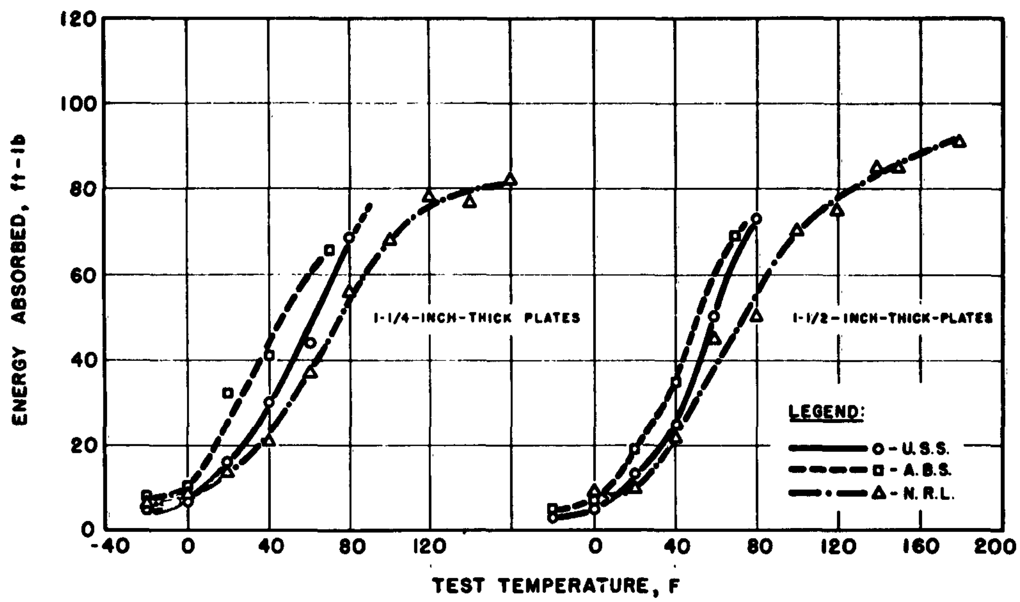

FIG. 13. CHARPY V-NOTCH CURVES FOR HEAT C, TESTED AT DIFFERENT LABORATORIES

test results from the three laboratories. The 15 ft-lb transition temperatures from the three laboratories are reported in Table 6.

Table 7 summarizes the V-notch Charpy transition temperature determinations for the seven heats. The average Charpy V-notch 15 ft-lb temperature of 23 F for the 1 1/2-in. experimental plate is higher than the Harris and Williams objective of 10 F maximum. The 1 1/4-in. plate, however, meets the objective.

Ferrite Grain Size

Ferrite grain size values are also shown in Table 7 and are plotted versus the 15 ft-lb transition temperatures in Fig. 14. An average line has been drawn through the average points for the three plate thicknesses. The slope of this line is 36 F per unit grain size number, which is somewhat higher than values cited in the past. However, the range of grain sizes is small and the data show appreciable scatter; hence, the slope cannot be considered precise.

Drop-Weight Tests

The crack-starter drop-weight test nil-ductility temperatures (NDT) are

TABLE 6

COMPARISON OF CHARPY V-NOTCH TRANSITION TEMPERATURES OBTAINED BY DIFFERENT LABORATORIES

Steel	Plate Thickness, in.	15 Ft-lb Charpy V-Notch Transition Temperature, F. USS	ABS	NRL	Average
A	3/4	-25	-22	-10	-19
	1-1/4	-8	-12	10	-3
	1-1/2	20	8	18	15
B	3/4	-30	-22	-10	-21
	1-1/4	-3	-16	5	-5
	1-1/2	13	10	10	11
C	3/4	-7			-7
	1-1/4	19	8	24	17
	1-1/2	28	16	32	25
D	3/4	-22, 2		-14	-11
	1-1/4	-18		-6	-12
	1-1/2	18		24	21
E	3/4	-14, 2		6	-2
	1-1/4	15		22	18
	1-1/2	30		22	26

NOTE: For the 1 1/2-inch-thick plates of Heats A, B, and C, the plate samples tested at USS were obtained from different plates than the plate samples tested at ABS and NRL (see Table 1). In all other cases, the different laboratories tested the same plates.

recorded in Table 8. It will be noted that, in addition to the tests on the full plate thickness, tests were also run on specimens of various reduced thicknesses that were machined from these plates. It is interesting to observe that the 3/4-in.-thick specimens from the 3/4-, 1 1/4-, and 1 1/2-in. plates gave the same average NDT, about 0°F, regardless of the as-rolled plate thickness. Tests using full-thickness specimens on the 1 1/4- and 1 1/2-in.

TABLE 7

CHARPY V-NOTCH TRANSITION TEMPERATURES AND FERRITE GRAIN SIZE

Heat	Charpy V-Notch Transition Temp, F, for Indicated Plate Thicknesses: at 15 Ft-lb, 3/4 in.	1 in.	1-1/4 in.	1-1/2 in.	at 50% Shear, 3/4 in.	1 in.	1-1/4 in.	1-1/2 in.	ASTM Ferrite Grain Size at Indicated Plate Thicknesses: 3/4 in.	1 in.	1-1/4 in.	1-1/2 in.
A	-19*	-20	-3	15*	24	42	40	50	7.0	6.8	6.5	6.2
B	-21*	-22	-5*	11*	30	30	48	36	8.0	8.2	7.5	7.0
C	-7	35	17*	25*	40	90	68	58	8.2	8.0	7.8	7.5
D	-11*		-12*	21*	51		56	40	8.0		7.7	7.3
E	-2*		18*	26*	44		58	54	7.4		6.8	6.5
F	-10		22	30	58		62	66	7.8		7.0	6.3
G	4		18	32	66		62	60	7.8		7.0	6.5
Avg.	-9		8	23	45		56	52	7.7		7.2	6.8

*Average values from USS, ABS, and NRL data, Table 6. All other determinations are based upon USS data.

TABLE 8

CRACK-STARTER DROP-WEIGHT TEST RESULTS

NDT at Indicated Plate and Specimen Thickness, F

Heat	Plate Thick., in. →	3/4		1	1-1/4				1-1/2			
	Specimen Thick., In. →	5/8**	3/4	1	5/8**	3/4	1	1-1/4	5/8**	3/4	1	1-1/2
A		0*	-10* 10	14	0*	0*	10*	20*	10*	-10* 3	10*	20*
B		0*	-10*	14	0*	-10*	0*	10*	10*	0* -5	10*	30*
C			0	24	0*	-10*	10*	20*	10*	0* -5	20*	30*
D		0*	0* 0 -10		10*	5			10*	10	10*	
E		0*	-10* 0 0		10*	0			10*	10	10*	
F			0			-10				0		
G			0			0				0		
	Average		-2			-3				2		

* Tests conducted by NRL; other tests by USS.
** Subsize specimens, 5/8 in. thick by 2 in. wide tested over 4-in. span. All other specimens were 3-1/2 in. wide and tested over 12-in. span.

NOTE: All NDT values were obtained using NRL normalization procedures[3] consisting of 0.3-in. deflection for 3/4- through 1 1/4-in.—thick specimens, 0.2-in. deflection for 1 1/2-in.—thick specimens, and 0.075-in. deflection for 5/8-in.—thick subsize specimens.

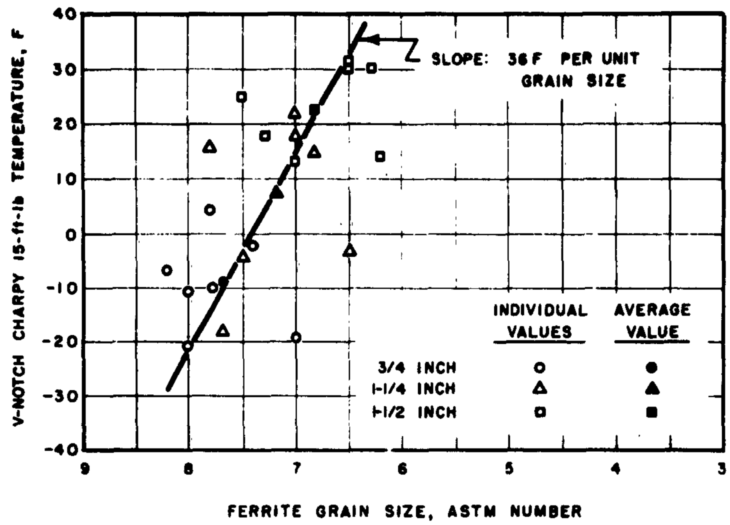

FIG. 14. INFLUENCE OF GRAIN SIZE ON TRANSITION TEMPERATURE.

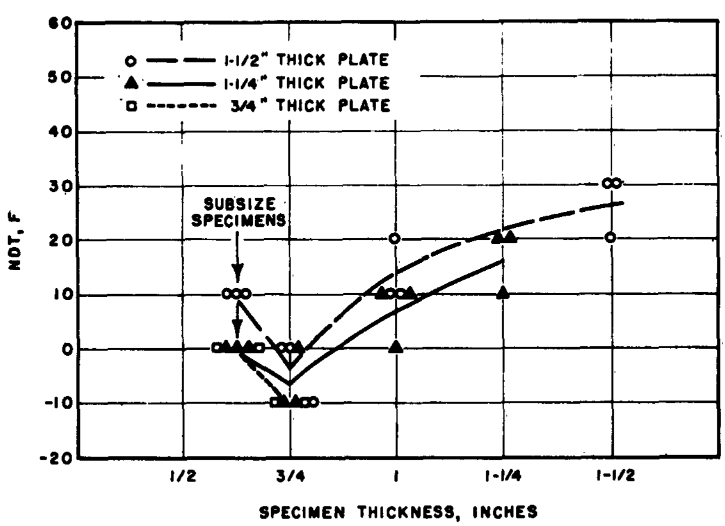

FIG. 15. EFFECT OF SPECIMEN THICKNESS ON DROP-WEIGHT NDT.

plates, however, resulted in noticeably higher NDT values. It is apparent that a specimen thickness effect exists in these drop-weight tests even though the prescribed normalization procedures[3] were used. An estimate of the specimen-thickness effect can be obtained by plotting specimen thickness vs NDT for each plate thickness, as in Fig. 15, which covers the NRL data on Heats A, B, and C. NDT is observed to decrease as the specimen thickness decreases to 3/4 in. The slight increase in NDT as the specimen thickness further decreases to 5/8 in. is apparently associated with the fact that the

latter specimen is subsize and of different dimensions than the others. The average change in NDT attributed to specimen thickness is as follows, using the 3/4-in. specimen as the reference thickness with an NDT 0°F.

Specimen Thickness, in.	NDT, F
5/8 (Subsize)	10
3/4	0
1	15
1-1/4	25
1-1/2	30

This consistent trend is definitely significant and should be taken into account wherever necessary. Of course, to evaluate these steels by the drop-weight test it must be decided whether it is more appropriate to use the full-thickness specimens or to use subsize specimens or specimens that have been machined down to some thickness such as 1 inch.* This will be discussed further later. For the present, the data will be analyzed based upon the results, either actual or extrapolated, for specimens of full-plate thickness.

Thus, in Table 8, for the tests on Heats D, E, F, and G where full-thickness specimens were not tested for the 1-1/4- and 1-1/2-in. plates, a correction must be applied to obtain the estimated NDT for full-thickness specimens. For example, where tests were conducted only on 3/4-in.-thick specimens from 1-1/4-in. plate, the corrected NDT for full-plate thickness will be

*Pellini has lately reduced the NDT test method to three specific sizes of drop-weight specimens, 5/8 x 2 x 5 in., 3/4 x 2 x 5 in., and 1 x 3 x 14 in. These specimens tested with appropriate stops are said to provide identical NDT values within the reproducibility range of ± 10 F assigned to the test method. The use of the 3/4 x 3 x 14 in. specimen has been discontinued because it consistently gives NDT temperatures approximately 15 F below those of the now-standard tests. This behavior is ascribed to excessive flexibility of the specimen. The use of 1-1/2-and 2-in. tests has also been discontinued in line with Pellini's concept that the extra thickness changes the test to one involving a large flaw size (the internal crack that forms before the specimen breaks across the surface). The larger flaw does result in increasing the NDT on the order of 20 to 30 F, but not higher because of the temperature effect on restricting the size of the internal flaw. In keeping with the intended use of the test as a small-flaw ductility-transition test, Pellini believes that analysis of the present report is best made in terms of the 5/8 and 1-in. tests.

obtained by adding 25 F to the NDT obtained with the 3/4-in.-thick specimens. An average correction may be applied for Heats D and E based upon the results obtained with the specimens of various reduced thicknesses. Corrected values are shown in Table 9 which lists the average NDT's obtained for the different heats for full-thickness specimens. The increase in transition temperature as plate thickness increases is similar to that obtained with the 15 ft-lb V-notch Charpy transition temperature. In the Charpy test, however, the specimen size remains constant and the increase in transition temperature is associated with metallurgical factors; in the drop-weight test the increase in NDT with increasing plate thickness largely results from the increase in specimen thickness.

Explosion Tests

The fracture transition temperatures for elastic loading (FTE), as determined by crack-starter explosion tests at NRL, are listed in Table 10. These tests were conducted on full-thickness plate samples. It will be noted that the average FTE increased only slightly as plate thickness increased. The NDT increased at a substantially more rapid rate with plate thickness when full-thickness specimens were used. As a result, the difference between FTE and NDT decreased as plate thickness increased. Data obtained at NRL on a variety of steels have indicated that FTE is usually about 40 F above NDT.[4] On Heats A and B, however, (the only heats in Table 10 on which full-thickness drop-weight tests were conducted on 1 1/2-in. plate) the actual difference between FTE and NDT for the 1 1/2-in. plates is 10 F. This observation would have to be related to service behavior to determine its true significance.

Tests on Normalized Plate

V-notch Charpy, drop-weight, and van der Veen notch-toughness tests and a few low-blow tests were conducted on normalized plates of the experimental steel from Heats A, D, and E. To provide the proper comparison, the van der Veen tests were also performed on the as-rolled product. The V-notch Charpy test results are presented in Table A-2 of the Appendix and the detailed van der Veen test results in Ref. 10. The transition temperature evaluations

TABLE 9

AVERAGE CRACK-STARTER DROP-WEIGHT NDT VALUES FOR FULL PLATE THICKNESSES

Heat	NDT, F, for Indicated Plate Thickness			
	3/4 in.	1 in.	1-1/4 in.	1-1/2 in.
A	0	14	20	20
B	-10	14	10	30
C	0	24	20	30
D	-3		28*	32*
E	-3		25*	32*
F	0		15*	30*
G	0		25*	30*
Average	-2		20	29

*Correction factor applied.

TABLE 10

CRACK-STARTER EXPLOSION TEST RESULTS

Heat	FTE, F, for Indicated Plate Thickness		
	3/4 in.	1-1/4 in.	1-1/2 in.
A	30	50	(30)
B	30	30	(40)
C		50	
D	40	(50)	(70)
E	(60)	50	(50)
Average	40	46	48

NOTE: Values in parentheses are less precisely determined than the other values.

are summarized in Table 11 for both as-rolled and normalized product so that results may be compared. Normalizing lowered the 15 ft-lb temperature an average of 16 F. The NDT for full-thickness specimens was improved an average of 38 F by normalizing, which is considered a very substantial improvement. In the van der Veen test, normalizing lowered the fracture-appearance transition

TABLE 11

TRANSITION TEMPERATURES ON NORMALIZED VERSUS HOT-ROLLED PRODUCT

Heat	Plate Thickness, inches	15 Ft-lb V-Notch Charpy Temperature, F: Hot-Rolled	Norm.	Improvement	Drop-Weight NDT, F: Hot-Rolled	Norm.	Improvement	van der Veen Fracture Appearance Temp, F: Hot-Rolled	Norm.	Improvement	Low-Blow Transition Temp, F Normalized
A	3/4	-19	-40	21	0	-40	40	34	0	34	32
	1-1/4	-3	-13	10	20	-22	42	74	44	30	
	1-1/2	15	14	1	20	-30**	50	96	37	59	
D	3/4	-11	-22	11	-3	-30	27	66	75	-9	68
	1-1/4	-12	-30	18	28*	-22	50	88	66	22	
	1-1/2	21	-4	25	32*	5**	27	103	84	19	
E	3/4	-2	-13	11	-3	-30	27	75	64	11	32
	1-1/4	18	14	4	25*	-22	47	116	66	50	
	1-1/2	26	-13	39	32*	-4**	36	108	59	49	
				16 Avg.			38 Avg.			30 Avg.	

*Correction factor applied, as in Table 9.
**0.3-inch deflection on 1 1/2-inch-thick specimens; hence, NDT is somewhat higher than if normalization procedure had been used.

TABLE 12

AVERAGE TRANSITION TEMPERATURES OF EXPERIMENTAL AND ABS STEELS

Grade	Plate Thickness, inches	Reference	V-Notch Charpy Test: No. of Plates	Temp at 15 Ft-lb, F	Temp at 50% Shear, F	Drop-Weight Test: No. of Plates	NDT, F	van der Veen Test: No. of Plates	Fracture Appearance Transition Temp, F	Crack-Starter Explosion Test: No. of Plates	FTE, F
ABS Class C, Normalized	3/4	13	3	-65		3	-23				
	1	4, 14	7	-26		7	-20			7	20
	1-5/8	9	4	-50							
ABS Class C, As-Rolled	1	4, 14	4	18		4	8				
	1 to 1-1/2	9	28	-18							
	1 to 1-1/2	11	Many	-8							
	1-1/4	12	49	-19 to -4	40 to 75	37	-7 to 20				
0.20 max C, 1.00-1.35 Mn Semikilled Production Heats, As-Rolled	3/4		9	-9	45	9	-2	3	58	4	40
	1-1/4		7	8	56	7	20	3	93	5	46
	1-1/2		7	23	52	7	29	3	102	4	48
0.20 max C, 1.00-1.35 Mn Semikilled Production Heats, Normalized	3/4		3	-25	19	3	-33	3	46		
	1-1/4		3	-10	22	3	-22	3	59		
	1-1/2		3	-1	38	3	-10++	3	60		
0.20 max C, 1.00-1.35 Mn Semikilled 25-Ton Heats, As-Rolled	3/4	2	2	-16	41	2	-15	2	51**	2	20
	1-1/4	2	2	-10	37	2	5	2	80**	2	35
	1-3/4	2	3	-3	49	3	25***	3	81**	3	42
1956 ABS Class B	3/4 to 1	*	6	6		2 (3/4")	5				
						2 (1")	20				
	3/4 to 1	9	19	-2							
	1/2 to 1	11	76	2							
	3/4	12	39	-1 to 12	43 to 61	30	-12 to 2				
1948 ABS Class B	5/8 to 1	9	11	25							
	1/2 to 1	11	Many	28							
	3/4	12	17	29	81						
	3/4	2	4	25		5	4				
	1	2	11	38		11	35				
1956 ABS Class A	1/2	11	Many	46							
ABS Before 1948	3/4	4, 9	Many	65		Many (3/4 to 1")	25			Many	70

*Unreported USS data.
**Data obtained by New York Naval Shipyard subsequent to issuance of report of Reference 2.
***Specimen thickness of 1-inch gave 7 F NDT. Correction factor of 18 F added.
++Somewhat high because 0.3-inch deflection was used.

temperature of the experimental plates 30 F. Improvements of different magnitude in the notch-toughness qualities of the experimental steel when normalized were thus obtained by the three testing techniques, with the smallest improvement obtained by the V-notch Charpy 15 ft-lb criterion.

In the normalized condition and in all thicknesses, this steel meets the Harris-Williams requirement of an average V-notch Charpy 15 ft-lb temperature no higher than 10 F.

The low-blow V-notch Charpy tests were conducted by Watertown Arsenal on normalized 3/4-in. plates, but similar tests were not performed on as-rolled product. On the average, these transition temperatures agree fairly well with those obtained on the same plates by the van der Veen test, but individual results are not in close agreement.

Comparison of Transition Temperatures

Table 12 is a summary of the average transition temperatures obtained in the different tests for the experimental steels and, for comparison, for the various ABS steels. Data on the two 25-ton heats of experimental steel previously tested[2] have been included in the table. It will be noted that van der Veen test data were not available for the ABS steels. Where a range of transition temperatures is shown, two or more sets of averages were available and the range indicates the spread in these averages. The NDT values listed are for full-thickness specimens. The only values in Table 12 that appear to be considerably out of line are the -26 F average 15 ft-lb temperature for normalized Class C steel and the 18 F 15 ft-lb temperature for as-rolled Class C. The same four heats of steel are involved in each instance, and the 15 ft-lb temperatures appear to be much too high compared to the other values. Despite the high 15 ft-lb temperatures, the NDT values agree fairly well with the other data on this grade. Because of this departure from apparently normal behavior, these particular V-notch Charpy 15 ft-lb temperatures for as-rolled and normalized Class C steel will not be considered in the forthcoming comparisons.

The V-notch Charpy 15 ft-lb temperatures and the NDT values in Table 12 are graphed in Figs. 16 and 17, respectively, to show the trend in behavior with plate thickness for the different grades of steel. In some cases, the

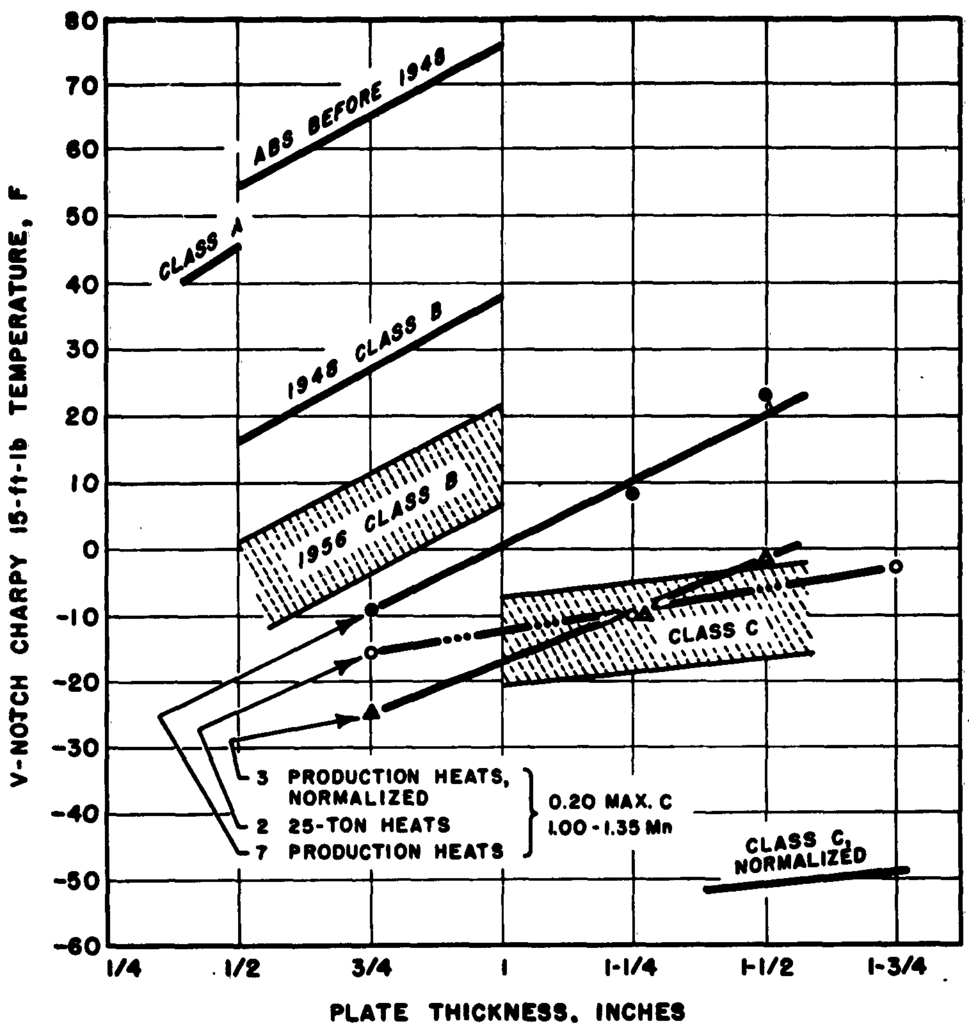

FIG 16. AVERAGE V-NOTCH CHARPY TRANSITION TEMPERATURES FOR EXPERIMENTAL AND ABS STEELS.

slopes of the lines for the ABS steels have been assumed, because data on specific different thicknesses were lacking.

Figure 16 shows that a 10 F maximum average 15 ft-lb temperature can be met for the experimental production heats in plate thicknesses up to approximately 1-1/4 in. Class B steel (1956), which is considered to have suitable notch toughness and has not suffered any brittle fractures in ship service, has an average 15 ft-lb temperature of 10 or 15 F for 1-in.-thick plates (although few data are available on plates of this specific thickness, there is much information on 3/4-in. plates 11--13 and there should be little error involved in

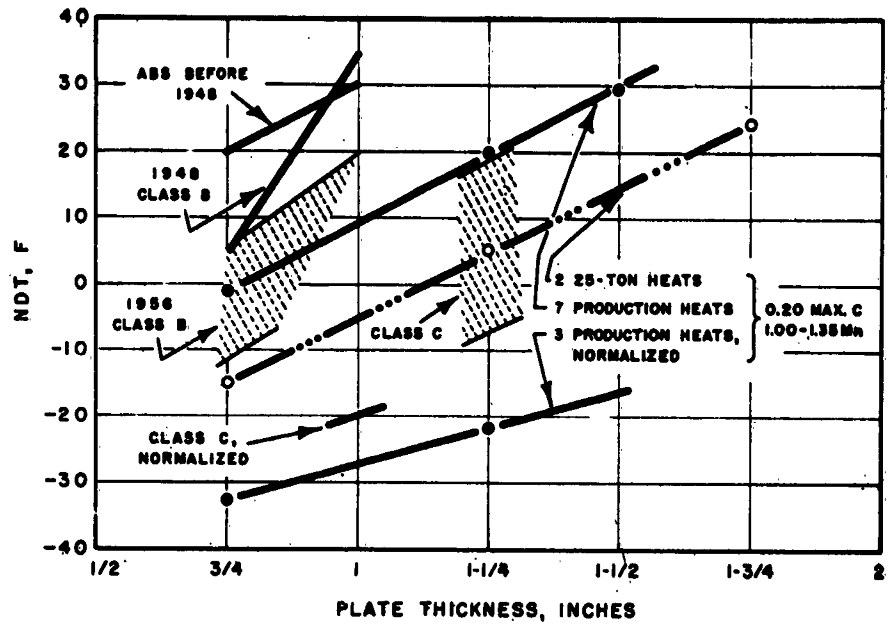

FIG. 17. AVERAGE DROP-WEIGHT TRANSITION TEMPERATURES FOR EXPERIMENTAL AND ABS STEELS.

extrapolating the results to 1-in. plates).

The two 25-ton experimental heats (discussed in detail in Ref. 2) are seen to have better 15 ft-lb temperatures than the seven production heats, but the reasons for the difference in behavior are not known. The 25-ton heats were made and processed at a different mill than the production heats, and subtle differences in practice might account for the differences in resulting behavior. The experimental steel, however, will be evaluated on the basis of the full-size production heats.

The as-rolled Class C steel has appreciably better 15 ft-lb temperatures than the experimental production heats, and the normalized Class C steel, which is generally used for plate thicknesses over 1-3/8 in., exhibits much-improved behavior.

The normalized experimental steels have about the same 15 ft-lb temperatures as the hot-rolled Class C steel.

Figure 17 is based upon full-thickness drop-weight-test specimens. With this interpretation, it may be seen that the drop-weight test rates the steels quite differently than the V-notch Charpy test. For example, by the drop-weight

test, 1 1/4-in. Class C steel has slightly poorer notch toughness than 3/4-in. 1956 Class B. The 1 1/4-in. experimental production plate has an NDT of 20 F, which is about 10 F higher than that of 1-in. 1956 Class B; in fact, by this test, the experimental steel is no better than 1956 Class B at equivalent thicknesses. The normalized experimental steel, however, is better than normalized Class C.

Underbead-Cracking Susceptibility

The average results of the underbead-cracking tests on the experimental production heats are listed in Table 13 as a function of the carbon equivalent, which was calculated as %C + %Mn/6.[14] These results for 0° and 70 F preheating temperatures are plotted in Fig. 18. Curves are also shown for the two 25-ton experimental heats, and the experimental production heats show slightly less underbead cracking than the 25-ton heats at equivalent C contents.

INTERPRETATION OF TEST RESULTS

In interpreting the test results, emphasis has been placed upon the results obtained on the seven full-size production heats rather than on the two 25-ton heats of experimental steel. As indicated previously, the reasons for the difference in behavior between these two groups of steel are not known.

Tension Tests

The tension-test results indicate that a suitable composition range for meeting the ABS tension-test requirements with the hot-rolled semikilled experimental steel would be 0.12 to 0.20% C and 1.00 to 1.35% Mn for plate thicknesses over 1 to 1-1/2 in.

V-Notch Charpy Tests

The suitability, with respect to notch toughness, of this steel for cargo-ship application is difficult to assess because of the different evaluations provided by different kinds of notch-toughness tests. Harris and Williams concluded that the ships would be virtually free from brittle fracture if constructed from plate with a maximum average 15 ft-lb V-notch Charpy transition temperature of 10 F. On this basis, Fig. 15 shows that the experimental steel could

TABLE 13

RESULTS OF UNDERBEAD-CRACKING TESTS

Heat	Plate Thickness, in.	Carbon Equivalent, %*	Per Cent Underbead Cracking** (With E6010 Electrodes) Initial Welding Temperature, F: 0	70	212
A	3/4	0.33	0	0	0
	1	0.35	0	0	0
	1-1/4	0.34	0	1	0
	1-1/2	0.30	0	3	0
B	3/4	0.37	3	8	0
	1	0.43	9	23	1
	1-1/4	0.37	3	2	1
	1-1/2	0.35	0	1	0
C	3/4	0.43	53	56	16
	1	0.47	32	27	3
	1-1/4	0.43	27	23	2
	1-1/2	0.42	5	10	3
D	3/4 Top	0.39	0	0	0
	3/4 Bottom	0.40	3	0	0
	1-1/4	0.42	0	0	0
	1-1/2	0.36	0	0	0
E	3/4 Top	0.35	0	0	0
	3/4 Bottom	0.35	0	0	0
	1-1/4	0.36	0	0	0
	1-1/2	0.33	0	0	0
F	3/4	0.42	25	23	3
	1-1/4	0.40	14	7	0
	1-1/2	0.38	22	21	0
G	3/4	0.39	8	6	0
	1-1/4	0.37	0	0	0
	1-1/2	0.34	4	0	0

*Carbon equivalent = %C + %Mn/6.

**Average of five specimens.

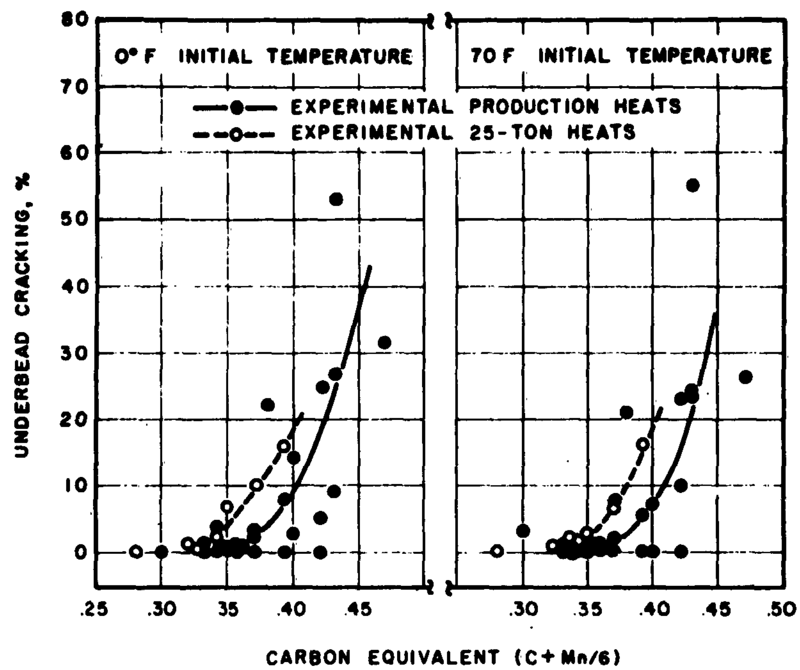

FIG. 18: EFFECT OF CARBON EQUIVALENT ON UNDERBEAD CRACKING TENDENCY FOR EXPERIMENTAL AND OTHER STEELS

be used in thicknesses up to 1-1/4 in., inclusive. Since ABS Class B steel is used in thicknesses to 1 in., inclusive, the experimental steel would find application in a very limited thickness range unless the ABS specification were revised to require the use of the experimental steel in thicknesses over 1/2 to 1-1/4 in., inclusive.

One-in.-thick 1956 Class B steel has an average 15 ft-lb temperature of 10 or 15 F, and experience to date indicates that this steel is quite satisfactory for ship service. This observation ties in very well with the Harris-Williams conclusion mentioned above.

Emphasis upon a V-notch Charpy 15 ft-lb criterion is based upon the service performance of ships constructed of World War II type ship plate. More recent data from actual service failures indicate that the Charpy impact energy needed to avoid brittle fracture in service will vary with the grade of steel.[4] For a number of grades of steel, the energy requirement seems to be greater than that developed for World War II ship plate. Thus, a 15 ft-lb

V-notch Charpy impact requirement based upon the reasoning used in the analysis of World War II ship fractures may be improper for assessing the suitability of other steels, such as the experimental steel, and could be insufficient to provide the protection required.

Drop-Weight Tests

Crack-starter drop-weight tests have gained increasing acceptance as a means for predicting brittle failure temperatures in service, because NDT values have corresponded to or have been higher than the temperatures at which failures have occurred in service.[15] Drop-weight tests provide a different relative evaluation of steels than do V-notch Charpy tests as may be noted by comparing Figs. 16 and 17. This means, in effect, that the energy level in the V-notch Charpy test at NDT varies with the grade of steel. If the drop-weight test is providing the proper evaluation of service performance, the 15 ft-lb level in the V-notch Charpy test is not necessarily the proper level for selecting a meaningful transition temperature.

Some aspects, however, of the drop-weight test results require further explanation. First, NDT did not increase as plate thickness increased if the drop-weight specimen thickness was kept constant (Table 8). NDT thus seems insensitive to grain size and other microstructural effects that have an appreciable influence on Charpy impact behavior. As specimen thickness increased in the drop-weight test, however, NDT was found to increase even when using normalization procedures (Fig. 15). This observation, which is definitely significant because it is based upon average behavior resulting from a number of observations, may raise some question as to the manner in which drop-weight tests should be conducted. It may appear that evaluations based upon full-thickness specimens, as in Fig. 17, would be the more appropriate. This, however, is not necessarily so. Puzak et al[15] show, in the case of a 7-5/8-in.-thick Ni-Mo-V pressure-vessel forging (Correlation Case No. 8), that the NDT for a specimen 6 x 7-5/8 x 60 in. is the same (130 F) as that for a specimen 1 x 3-1/2 x 14 in. A specimen 1-1/2 x 3-1/2 x 14 in. of the same steel actually had a 10 F higher NDT. The length of the specimen or the span over which it is tested thus seems to be influencing the test results. It appears that NDT

may not increase with specimen thickness provided the test span is increased at the same time.

In a recent publication, Pellini et al[16] point out that large flaws will permit initiation of brittle fracture above the usual NDT temperature. In a private communication, Pellini has stated that the relatively high NDT values for a 1-1/2-in.-thick specimen tested over a 12-in. span may be associated with the development of a larger flaw when the specimen is bent than would usually be experienced in ship structures. This large flaw would permit crack propagation completely across the specimen and thus indicate a higher-than-usual NDT. Where relatively small flaws are usually involved, Pellini now prefers to base the NDT determination upon either subsize specimens tested over a 4-in. span or upon 1-in.-thick specimens tested over a 12-in. span regardless of the original plate thickness. Additional large-scale testing will undoubtedly be needed to resolve this point, but it seems only fair to recognize this approach in analyzing the present data.

First, the full-thickness drop-weight-test results of Fig. 17 will be considered. It will be noted that the production heats of experimental steel have no better toughness than 1956 Class B steel when their thicknesses are comparable as at 3/4 in. Experience indicates that the 1956 Class B is quite suitable for cargo-ship service, and its extrapolated average NDT for 1-in. plate is about 10 F (fortuitously, this is also the maximum temperature specified by Harris and Williams for the average V-notch Charpy 15 ft-lb temperature). It would therefore seem logical to have as an objective an average NDT no higher than 10 F for the experimental steel. On this basis, the experimental steel could not be used in any greater thickness than the Class B steel. Indeed, the Class C steel is only slightly tougher than the Class B, and it appears it would have an average NDT of 10 F at a thickness of approximately 1-3/8 in. No data are available for Class C in the normalized condition for thicknesses over 1 in., but it looks (Fig. 17) as though a 10 F NDT would not be obtained for the normalized product until the plate thickness reached at least 1-3/4 in. ABS Class C steel is usually normalized for ship applications when the plate thickness exceeds 1-3/8 in. Based upon this method of analyzing the drop-

weight test results, this seems to be the correct procedure to follow for plates over 1-3/8 in. thick to develop toughness. Based upon Charpy results, however, normalizing of Class C steel would not be necessary to maintain an average 15 ft-lb transition temperature of 10 F maximum in thick plate.

Next, the drop-weight-test results for 1-in.-thick specimens will be considered as advocated by Pellini for small-flaw defects. Appropriate NDT values for 1-in.-thick specimens may be derived by applying appropriate corrections such as listed on page 17 to the NDT values in Fig. 17 for full-thickness specimens. When this is done, the following NDT values for 1-in.-thick specimens are obtained:

Grade	Thickness, in.	NDT, °F
1956 Class B	1	10
Experimental steel	1 to 1-1/2, incl	10 to 15
ABS Class C	1 to 1-3/8, incl	- 5 to 0
(as-rolled)		
(norm)	1 to 1-1/2, incl	-20 to -25

On this basis, the experimental steel appears to have just about sufficient notch toughness to allow its substitution for ABS Class C in thicknesses to 1-1/2 in. An average NDT of 10 F is assumed to be satisfactory and the NDT for the experimental steel is 10 to 15 F. It should also be pointed out, however, that 1956 Class B steel might also be suitable in heavier thicknesses since, at thicknesses of 3/4 to 1 in., inclusive, it exhibits essentially the same behavior as the experimental steel. This is not too surprising because a report,[17] based upon compositional differences, shows that the NDT of the experimental steel should be only 6 F lower than that of 1956 Class B. The main compositional difference in these two steels is the Mn content, which was found to have a much less effect upon NDT than upon the V-notch Charpy 15 ft-lb temperature.

Tests on Normalized Plate

Normalized steel from the experimental production heats performed about as well as hot-rolled Class C steel according to the Charpy tests and even better than normalized Class C steel according to the drop-weight tests.

The latter observation is surprising for normalized Class C has about a 50 F lower V-notch Charpy 15 ft-lb temperature than the normalized experimental steels. Thus, according to both tests, the normalized experimental steel could be used in place of as-rolled Class C steel. However, the requirement of normalizing would be an undesirable feature in view of the fact that the Class C can be used in the as-rolled condition up to 1-3/8 in. thick. Actually, present economics would favor the use of the killed, hot-rolled, Class C steel instead of the semikilled, normalized, experimental steel. Over 1-3/8-in. thickness, it may be problematical as to which normalized steel would be better because of the extreme divergence of the test results. It does appear, however, that either the normalized Class C or the normalized experimental steel would have sufficient toughness to perform quite satisfactorily in thicknesses up to at least 1-3/4 in.

Fracture Transition Temperatures

The van der Veen tests gave high transition temperatures that were well above the FTE values determined by the crack-starter explosion tests. The van der Veen transition temperatures were, on the average, about 70 F higher than the NDT values, whereas the FTE values were only about 45 F higher than NDT for 3/4-in. plate and appreciably less than 45 F for the heavier plates (when using full-thickness drop-weight specimens). The explosion test has provided a fairly good correlation with crack arresting ability in wide plate tests in some other studies,[2,18] and it is believed that the van der Veen tests are giving a less favorable evaluation of crack propagation behavior than is justified.

On the average, the low-blow transition is the same as the van der Veen (Table 11), but the individual comparisons show appreciable scatter for the three plates involved. There are too few data to draw any conclusions regarding these low-blow test results.

The V-notch Charpy 50% shear temperatures agree fairly well with the FTE values for the experimental steels. According to the Charpy tests, the experimental steel, the as-rolled Class C steel, and the 1956 Class B steel all have about the same fracture transition temperature. Suitable explosion-test

data are lacking for as-rolled Class C, but, assuming a 40 F difference between FTE and NDT, the FTE would be about 45 F or the same as that for the experimental steel.

Based upon the limited comparative data available, it thus appears that the experimental steel and Class C steel in the as-rolled condition would have about the same crack stopping ability and would arrest cracks at temperatures above approximately 45 F. It is estimated that these steels would also have about the same crack-arresting ability in the normalized condition (arresting cracks above approximately 20 F).

Underbead Cracking

The average C equivalent for the experimental steel made to 0.20% maximum C and 1.00 to 1.35% Mn content would be about 0.35 and the maximum based upon these composition limits would be 0.43. Winterton[14] points out that available data indicate that welding precautions are generally advisable when the C equivalent exceeds 0.39. Figure 18 certainly is in agreement with this observation. Welding precautions might therefore be needed for the experimental steel when the C equivalent is 0.40 or higher. This would involve the use of low-hydrogen electrodes or preheating when welding with cellulose-coated electrodes.

For Class C steel, the average and maximum C equivalents are about four points lower than those for the experimental steel because of the difference in Mn contents. Hence, welding precautions would not seem necessary for Class C steel. Experimental data would be needed to verify this conclusion for C equivalents will not precisely reflect the actual cracking obtained. Actual shipyard welding procedures are, of course, already established for this grade.

SUMMARY AND CONCLUSIONS

V-notch Charpy and drop-weight tests were conducted on seven heats of an as-rolled semikilled steel containing 0.20% maximum C and 1.00 to 1.35% Mn content to determine its suitability as a substitute for as-rolled Class C steel in thicknesses over 1 in.

Based upon the Harris-Williams conclusion that an average V-notch Charpy 15 ft-lb temperature of 10 F maximum would assure virtual freedom from brittle fracture in ships, the experimental steel would be satisfactory in plate thicknesses up to 1-1/4 in., inclusive. From Fig. 16, the 15 ft-lb temperature of 10 F for 1 1/4-in. plate is slightly lower than that of 1-in.-thick ABS Class B steel but about 20 F worse than that of 1 1/4-in. Class C.

The V-notch Charpy 15 ft-lb temperature and the drop-weight-test NDT do not, however, give the same relative evaluations of performance, and it is appropriate to take the results from both tests into consideration at this time.

When using full-plate-thickness drop-weight-test specimens, the NDT of 1-1/4-in. plate of the experimental steel is about 10 F worse than that of 1-in. Class B and 15 F worse than that of 1-1/4-in. Class C. On this basis, the experimental steel would not quite have sufficient notch toughness to be considered a suitable substitute for as-rolled ABS Class C steel in thicknesses over 1 in.

When using 1-in.-thick drop-weight-test specimens as advocated by Pellini to simulate small flaws, the NDT of the experimental steel for all thicknesses up to 1-1/2 in., inclusive, is just about the same as that of 1-in.-thick ABS Class B steel. Hence, with this interpretation, the experimental steel should have just about sufficient notch toughness to allow its use as a substitute for Class C steel in thicknesses over 1 in. Since ABS Class B steel and the experimental steel have similar NDT values in equivalent thicknesses, it is also possible that Class B steel would be sufficiently tough to use in thicknesses up to 1-1/2 in., inclusive.

Because of these contradictory indications from the different notch-toughness tests and from different interpretations of the same test, a firm conclusion on the suitability of the experimental steel as a substitute for ABS Class C cannot be reached at this time. The problem is difficult in this instance because of the need to resolve small differences in transition temperature evaluations on the order of only 10 or 20 F. Development of a small-scale test and testing technique that could properly assess such refinements in notch-toughness behavior will require, for comparison, suitable large-scale testing

that would simulate behavior in service.

Normalizing the experimental steel provides suitable notch toughness by all test criteria, but there would be no economic advantage over as-rolled Class C steel. It does appear, however, that the normalized experimental steel would be a suitable and economical substitute for normalized Class C steel, which is used in thicknesses over 1-3/8 in. This substitution could, however, be a complicating feature since a favorable choice of steels might then involve as-rolled Class C for thicknesses to 1-3/8 in. and the normalized experimental steel for thicknesses over 1-3/8 in.

The above comments and conclusions are based upon notch-toughness tests that predict crack-initiation tendencies. Only limited comparative test data are available for estimating crack-arresting ability, but it appears that the experimental steel would be about as suitable as ABS Class C steel in this respect.

The composition limits of 0.20% maximum C and 1.00 to 1.35% Mn gave tensile properties that met ABS requirements for as-rolled plate over 1 to 1-1/2 in. thick.

Welding precautions might be needed for the experimental steel when the C equivalent (C + Mn/6) is 0.40 or higher. This would involve the use of low-hydrogen electrodes or preheating when welding with cellulose-coated electrodes.

A substantial effect of specimen thickness upon NDT was found in the drop-weight test even when using so-called normalization procedures. Full-thickness specimens from 1-1/2-in. plate had NDT's that were 30 F higher than those of 3/4-in.-thick specimens cut from the same plate. It is believed that further small-scale and large-scale testing is needed to determine the most suitable specimen dimensions for evaluating the actual service performance of plates over 1 in. thick.

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TABLE A-1

USS V-NOTCH CHARPY IMPACT TEST RESULTS ON AS-ROLLED EXPERIMENTAL STEEL

		3/4 Inch		1 Inch		1-1/4 Inch		1-1/2 Inch	
Heat	Test Temp, F	Energy Absorbed, Ft-lb	Shear Fracture, %	Energy Absorbed, Ft-lb	Shear Fracture, %	Energy Absorbed, Ft-lb	Shear Fracture, %	Energy Absorbed, Ft-lb	Shear Fracture, %
A	60					182,157,195	98,80,98	135,34,92	75,50,55
	40	114	60	107	65	95,97	55,45	109,23,39	75,50,40
	30			97,13,94	40,15,45				
	20	105,105	55,55	96,12,98,28	40,25,50,25	10,13,93	10,10,10	11,22,13	20,20,25
	10			15,58,92,58	15,20,40,20				
	0	11,87,27	10,30,10	12,9,82,9	15,15,40,15	8,7,73	15,10,30	6,9,12	15,15,20
	-20	7,86,9	10,30,10	4,57,20	5,15,5	5,4,7	10,5,5	4,6,6	15,10,10
	-30	9,6,5	5,5,5	4,2,3	3,2,3				
	-40	4,28,4	5,10,5	4,3,3	5,3,3				
	-60	2,7,3	3,3,3						
B	85					102,115,137	98,65,75	115,131,110	75,70,90
	80	120,120,120	80,80,80	72,79,82	70,80,80				
	60	120,116,114	80,70,75	49,74,55	50,65,60	53,100,89	55,60,65	89,132,95	65,90,70
	40	112,109,111	65,60,60	41,55,57	50,55,55	73,90,80	50,45,40	40,34,35	55,55,55
	20	72,67,22	45,45,35	41,42,40	45,45,45	58,39,83	25,20,45	19,27,17	30,35,30
	0	10,79,21	20,35,25	42,37,38	30,30,30	34,11,9	10,10,10	8,8,10	10,10,15
	-20	9,47,8	20,25,10	16,11,21	15,15,15	3,5,6	5,5,5	6,4,6	10,5,10
	-30	5,54,9	5,15,5	11,7,13	10,10,10				
	-40	6,5,5	5,5,5	5,4,10	5,5,10				
C	140			69,66,53	70,70,70				
	120			70,44,53	80,60,60				
	100			51,50,44	55,55,55				
	85					63,76,68	55,60,60	70,64,85	60,60,65
	80	77,82,80	70,75,70	39,37,22	45,45,45				
	60	62,61,61	60,60,55	37,33,35	45,45,45	42,44,45	45,45,45	46,57,46	50,50,55
	40	47,53,49	50,50,50	14,11,9	25,30,20	37,23,30	30,35,40	22,21,28	40,45,35
	30			15,27,12	20,25,20				
	20	34,16,33	40,35,40	14,8,9	20,20,15	12,13,23	20,20,25	12,13,13	20,20,25
	0	19,25,26	30,30,25	4,9,7	5,10,8	7,6,9	10,10,10	6,6,7	10,10,10
	-10	13,8,11	10,15,10						
	-20	10,8,9	15,15,15			4,4,5	5,5,5	5,4,4	5,5,5
	-40	5,3,6	5,5,5						
D	100			66,73,63	70,70,70			129,100,104	100,80,85
	80	96,90,99	75,75,85	59,66,67	55,60,60	73,67,72	65,60,50	90,107,120	60,75,100
	60	87,110,93	65,70,70	49,44,38	50,45,45	67,90,74	55,60,50	104,84,57	70,60,55
	50			50,40,38	45,45,40				
	40	66,83,68	50,50,40	40,47,42	40,45,40	79,46,81	55,35,60	78,17,93	55,30,70
	30							84,67,16	60,40,25
	20	61,50,31	35,30,30	31,25,23	30,25,25	41,51,58	20,20,25	8,10,29	15,20,20
	10							7,41,46	15,20,20
	0	9,51,47	20,25,25	10,21,7	15,15,15	13,8,32,30, 41,22	10,15,10, 15,15,15	13,6,8	10,10,10
	-10	16,31,13	15,20,15			26,15,30	5,5,5		
	-20	40,4,7,9, 25,38	20,10,10,5, 10,10	8,13,7,9, 7,8	10,10,10,5, 5,5	3,11,5,9,34, 6,17,18,19	5,5,5,10, 10,5,5,5,5	4,4,4,8	5,5,5,5
	-30	5,7	5,5			4,5,28,4,8,8	5,5,5,5,5,5		
	-40	6,6,5	5,5,5	4,6,7	5,5,5	9,9,5,3,5,5	5,5,5,5,5,5		
E	100	139,125,117	90,80,80	85,57,63	80,75,70	116,105,128	85,70,100	80,58,87	70,65,70
	80	130,123,107	80,80,80	58,49,64	60,55,60	97,79,85	65,60,65	87,57,65	80,70,60
	70							72,88,78	60,95,70
	60	126,114,125	75,65,75	41,49,38	50,50,45	80,66,97	50,45,60	20,40,61	40,45,50
	50							41,15,67	50,40,60
	40	110,89,113	65,60,65	37,37,36	45,45,50	51,11,34	30,25,30	26,16,67	35,40,50
	30					77,14,12	50,35,30	17,13,11	30,30,25
	20	91,42,49	50,35,35	37,18,29	35,25,25	10,7,13	20,20,20	11,10,10	30,30,30
	10					12,21,9	15,10,15		
	0	10,51,19	15,20,15	16,11,13	10,15,15	11,6,15	10,10,5	6,7,7	10,10,10
	-10	10,11,12	15,15,10	7,11,9	5,10,10	8,5,5	10,5,5		
	-20	67,27,7,8, 6,7	25,10,5,10, 10,10	12,17,7,6, 7,9	5,5,5,5, 5,5	5,3,3	5,5,5	5,6,4	5,5,5
	-40	3,3,5	5,5,5	4,3,4	5,5,5				

TABLE A-1 (Continued)

Heat	Test Temp, F	3/4 Inch Energy Absorbed, Ft-lb	3/4 Inch Shear Fracture, %	1-1/4 Inch Energy Absorbed, Ft-lb	1-1/4 Inch Shear Fracture, %	1-1/2 Inch Energy Absorbed, Ft-lb	1-1/2 Inch Shear Fracture, %
F	140	88,94,95	95,90,90	112,115	100,90	92,92,99	98,90,98
	120			118,107,105	95,90,90	96,94,90	99,90,90
	100	82,85,88	80,75,75	98,95,110	70,70,90	91,80,88	85,75,75
	78	67,81,75	50,70,60	79,84,91	60,60,60	78,68,63	70,70,70
	60	60,47,37	20,20,20	83,25,90	60,30,60	39,31,29	40,40,40
	40	56,44,48	45,40,40	25,48,15	30,40,30	23,17,18	30,30,30
	20	39,42,28,34 13,26	35,35,30,10 15,10	12,10,14	20,20,20	13,11,12	20,20,20
	0	30,11,14	20,20,20	14,8,7	15,15,15	6,6,6	10,10,10
	-10	15,6,31	50,45,45				
	-20	5,4,8	10,10,10	5,6,4	10,10,10	3,3,4	5,5,5
G	140	89,92,94	97,95,97	103,117,114	90,100,100	116,100,98	100,98,96
	120	86,90,80	85,85,85	105,108	90,85	100,104,108	85,90,90
	100	68,70,80	80,70,80	100,94	75,80	108,61,92	85,70,80
	78	57,71,72	65,65,65	88,76,92	60,55,60	39,70,74	55,65,65
	60	46,48,48	40,40,40	37,96,31	40,65,40	27,27,21	50,50,50
	40	20,50,30	25,35,30	71,60,40	35,35,25	18,19,16	45,45,45
	20	21,35,20	30,20,20	16,19,14	20,20,20	9,11,12	20,20,20
	0	6,13,15	5,10,10	5,5,6	15,15,15	6,5,5	10,10,10
	-20	5,4,9	5,5,5	4,3,3	10,10,10	3,4,3	5,5,5

TABLE A-2

WATERTOWN ARSENAL V-NOTCH CHARPY IMPACT-TEST RESULTS ON NORMALIZED EXPERIMENTAL STEEL

		3/4 Inch		1-1/4 Inch		1-1/2 Inch	
Heat	Test Temp, F	Energy Absorbed, Ft-lb	Shear Fracture, %	Energy Absorbed, Ft-lb	Shear Fracture, %	Energy Absorbed, Ft-lb	Shear Fracture, %
A	104			200	100	192	100
	95					200	100
	84	*	100			*	100
	77					24,45	30,60
	68					60	50
	50			139	100	28,*,*	40,100,100
	32	*	100	*	100	14,*,*	25,100,100
	14			179	100		
	5			141	80		
	-4	*	100	55,83	15,30	8	15
	-13	185	100				
	-22	81	20	11,9	30,25		
	-31	83,47,58,55	20,10,15,15	5	5		
	-40	53,5,6,10	20,5,5,10	5,64,3	5,20,5	6	5
	-58			3	5		
	-76	5	0	7	0	2	0
	-112			2	0	2	0
D	176					126	100
	158					126	100
	140	131	100	131	100	107	75
	122					116	80
	104	135	100	138	100		
	84	117	85	121	85	98	65
	68			127	85	90	45
	50	89	60			71	25
	32	81	55	106	65	23,17,99	20,25,50
	14					91,89	50,40
	-4	55,67	15,20	69	20	90,6	35,10
	-22	51,55,8, 10	10,10,10, 5	44,42	10,10		
	-31	7,8,3	5,5,5	18,12,5	5,5,5		
	-40		5	4	5	7	5
	-76	4	0	3	0	2	0
E	176			138	100		
	140			113	90		
	122			148	100		
	104			101,82	75,65		
	84	187	100	95,87	65,60	134	100
	77					154	100
	68			39,97	45,65	142	100
	59	179	100			106	70
	50	88	45	18,113,97	30,80,65		
	32	74,75	30,30	70	40	99	65
	14	60	15			80	40
	-4	64,9,12,39	20,10,15,15	6	15	74,74	25,25
	-13	9,11	10,15			8,27,11,15	10,10,15,15
	-22					8	10
	-40	5	5	3	5	3	5
	-76	2	0	2	0	2	0

*Specimen did not break--stopped pendulum.